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QUANTITATIVELY THE RESIDUAL
STRAINS IN METAL PLATES
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OBJECT

The object of this investigation is to
determine the possibility of measuring quantitatively
the residual stresses in metal plates by means of
brittle lacquer. It is known that the residual
stresses can be determined qualitatively by use of
the brittle lacquer from the work of previous in-
vestigators. This investigation will concern itself
with correlating the size of the pattern formed in
the lacquer on the release of the residual stresses
with the actual value of the residual stresses in
the metal.

IMPORTANCE

There is a great need for a simple yet
accurate method for determining the residual stresses
in a member without actually destroying the member or
the structure containing the member. If it were pos-
sible to determine the magnitude of the stresses by
the use of brittle lacquer, the simple and inexpensive
method needed would have been found. The work of
previous investigators has shown that the presence
and type of residual stresses can be found by the
use of brittle lacquer. In order to be of greatest
use, however, the quantity of stresses present should
be known. The brittle lacquer could then be used as
a method of testing a member after it has been placed
in a structure.

It is known that a member containing residual
stresses will yield under a smaller load than a member
free from residual stresses. If each structural mem-
ber could be designed as if free of residual stresses,
the weight of steel necessary would be greatly reduced.
Naturally, no structure could be built without inducing
residual stresses, but the amount of stresses could be
greatly reduced by proper sequence of construction or
other precautions. The members could be tested after
erection to see if they conformed to the design speci-
fications.

PROBLEM

The investigation resolved itself into
the following problem: To correlate the patterns
formed by drilling a small hole in a lacquer-coated
metal piece as described in references "A" and "B"
with the values of the residual strains found by
some other method. It was decided to measure these
residual strains by placing a wire strain gage on
the metal sample which contained residual stresses
and then cutting the gage away. The corrected
difference between the Strain Indicator reading
before and after the cutting would be the value
of the residual strain.

THEORY

The formation of the strain patterns is the result of drilling a hole in the metal. In the case of residual tension, the relief of the strain allows the metal to contract and radial cracks are formed. Whereas, with the relief of compressive forces, the metal expands and attempts to fill the hole causing circular cracks to form concentric to the hole. These theoretical patterns are shown on Plate I.

The same thing would happen when the strain gages are cut out. Relief of tensile strains would cause the metal to contract and compressive strains, when relieved, would cause the metal to expand. The gages when cut away measure 1.8" x .45"; thus the difference in the readings of the gage is actually (.45 - 1.8u) x the actual residual strain in the piece.

Since the amount of metal effected increases as the square of the distance from the hole increases, the length of the crack should increase as the square of the residual strain. Also, the larger the hole made, the greater the quantity of strain relieved. The quantity of strain will vary with the diameter of the hole. Therefore, in plotting the results,

the square root of the length of the crack divided
by the diameter of the hole was plotted against
the residual strain.

PLATE I
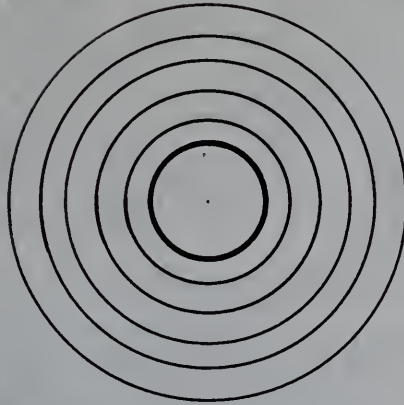
COMPRESSION
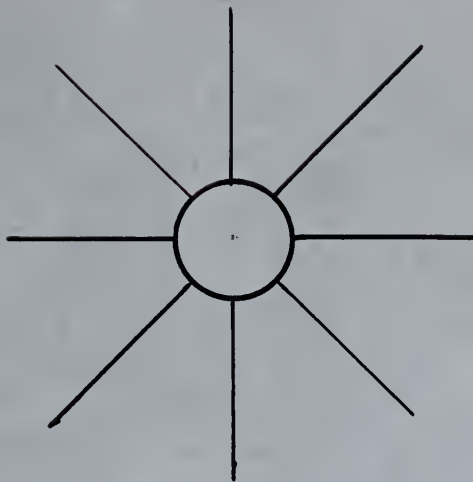
TENSION

THEORETICAL PATTERNS

PLATE I

PROCEDURE

General

The procedure followed in this investigation
was that recommended by the Magnaflux Corporation,
manufacturers of Stresscoat. This procedure was as
follows:

1. Spray test sample with brittle lacquer.

2. Drill small hole into test piece.

3. Apply dye etchant to lacquer.

4. Investigate pattern of residual stress
   present in the test sample at the place
   of the hole.

In the following investigation it was en-
deavored to determine the amount of residual strain
present by measuring the size of the pattern formed
in the brittle lacquer with the release of the residual
strain. In order to obtain a high sensitivity a lacquer
two or three numbers above that recommended by the
Magnaflux Corporation was used. The samples were
dried for 24 hours in an oven at 100 to 110 degrees F.
in order to prevent crazing.

The procedure used to determine the actual
residual strain was as follows:

1. Cement electric strain gage, type SR4a,
   as close to the hole as practicable.

2. Obtain initial strain reading.

3. Cut the strain gage from the sample.

4. Obtain final strain reading and
   determine the value of the residual
   strain.

The results were then plotted on Plate II.

HISTORY OF THE EXPERIMENT

In order to obtain high residual strains
which would be fairly uniform throughout the sample,
it was decided to use a heat-treatable steel as our
test sample. SAE 8630 steel was selected for this
purpose. The samples were cut from a normalized
strip of steel and measured 10" x 2" x 1/16". A
sample 1/8" thick or thicker would have been better
for this purpose because less distortion would have
occurred when it was quenched. The samples were
soaked for thirty minutes at 1500 degrees F. Some
were then quenched in water and some in oil to obtain
different hardness values and, therefore, different
strain values. The samples were then tested for ease
of drilling. The water-quenched samples were too
hard to drill with either plain carbon or high speed
drills, but they could be drilled with a specially
treated plain carbon drill. This treatment of the
drill consisted of heating for fifteen minutes at
1500 degrees F. and quenching it into mercury. The
above treatment produced a very hard but very brittle
drill. The oil-quenched samples could be drilled
with high speed drills. It was decided to discard
the water-quenched samples and to concentrate on the
oil-quenched samples because the specially treated
drills were too brittle for continuous use.

A large number of pieces were then heat-
treated and sprayed. Using a number 40 high speed
drill, several holes were drilled in each sample.
Patterns were observed and measured in most of the
pieces. The best patterns were photographed.
Examples of the patterns are shown in the photo-
graphs included as part of this thesis.

SR4a wire strain gages, type A-1, were
placed on the pieces near the holes showing the
patterns. Initial readings were taken on the gages
and then, using shears, the gages were cut out of
the sample. Again readings were taken on the gages
and the values of residual strains were computed.
Comparison of the residual strains with the length
of cracks in the brittle lacquer showed erratic
results.

After examination of the test results, it
was decided that the method of cutting the gages out
of the pieces was introducing excessive additional
strain in the samples. Therefore, a test was carried
out to find the magnitude of the strains induced in
the samples by three different methods of cutting;
namely, the shears, the power hack saw, and the hand
hacksaw. A fourth method, the use of a water-cooled
cutting wheel, was discarded after consultation with
Mr. Walter Koonradt, Metallurgy and Welding Department,

Rensselaer Polytechnic Institute. He advised
that the wheel could not be adjusted accurately
enough to cut closely to the strain gage and that
the vibration from the wheel would tend to loosen
the gage on the sample. The test for the first
three methods consisted of placing three strain
gages on normalized samples and then cutting them
away by the various methods. The shears induced
strains to the order of 1000 micro-inches; the
power hacksaw 100 micro-inches; and the hand hack-
saw 50 micro-inches. On the basis of this test,
it was decided to use the hand hacksaw for cutting
out the strain gages. However, it was almost im-
possible to cut the treated steel with either the
hand or the power hack saws. At this point, it was
apparent that cutting away electric strain gages to
find the residual strain was not satisfactory for
use with a material such as steel or any other
material which has high hardness accompanying the
high residual strains necessary for this investig-
ation.

Aluminum, which can be made to have high
residual strains without high hardness, was selected
for the next tests. The samples were pieces of
24S-0 Aluminum 2" x 6" x 1/8" which were heat-
treated for thirty minutes at 925 degrees F. and

quenched in cold water. Twenty pieces were sprayed
and then tested by drilling holes with a 3/32" drill.
Patterns were observed on only two pieces. Gages
were placed near the holes where patterns were present
and strain readings were taken. The gages were then
cut out of the samples by a hand hacksaw and strain
readings were taken again. Because of the small
number of pattern formations observed, it was de-
cided to cold-work the next group of aluminum sam-
ples. The samples were cold-rolled with a maximum
reduction of 60%. The spraying procedure was repeated
on these samples and the holes drilled with a 3/32"
drill. No patterns were observed. Gages were placed
on several of the pieces to find the actual residual
strains present in order to determine the threshold
sensitivity of the brittle lacquer method. These
gages were cut away and the strains recorded.

Dowmetal was the third metal tried for
this experiment. Twenty samples, reduced 13% by
cold-rolling, were sprayed and drilled. In two of
these pieces, patterns were observed. These were
the first compressive cracks found in this investig-
ation. Although the patterns were not well enough
defined to photograph, the cracks and the residual
strains were measured and recorded in the usual
manner.

Due to the lack of time, it was impossible
to attempt any further investigations. However, it
is felt that there is sufficient justification for
further tests. Accurate conclusions should be ob-
tained with an improved method of finding the actual
residual strains.

RESULTS

The results of the tests are tabulated
in Table I. There are some glaring inconsistencies
in the relationship between the size of the patterns
and the measured residual strains. In the case of
the steel specimens, one gage (gage 5) showed a
compressive residual strain, but all of the patterns
observed on the steel samples were tensile patterns.
Also, on the Dowmetal samples, which showed all com-
pressive patterns, gage 23 gave a tensile reading.
All of the data obtained from the steel samples must
be considered worthless because of the unpredictable
high shearing stresses induced as a result of the
method used in removing the gages from the samples.
There is not sufficient data from the lighter metals
to form a definite conclusion.

The findings from the aluminum and Dowmetal
tests are plotted on Plate II. They show nothing
conclusive inasmuch as they are too few in number
and are quite dispersed. The residual strains
found in the pieces in which no pattern resulted
were quite high and cast some doubt on the validity
of the brittle coating method even as a qualitative
indicator.

TABLE I

Group	Piece	Hole	Length of Line	Gage	Reading Before	Reading After
		1	No results			
		2	No results			
		3	1	.09	1	5-1795	7-1794
			2	.10			
			3	.06	2	5-1030	
			4	.08			
			5	--	3	5-0801	7-0949
			6	.08			
		4	1	.18	4	5-1888	9-0801
			2	.10			
			3	.09	5	6-1228	4-1519
			4	.09	6	6-1419	
			5	.10			
			6	.13	7	6-1579	9-0977
			7	.13			
A	1	No results				
	2		.04	12	5-0885	5-1483
				13	6-0758	8-1599
	3		.08	14	7-1075	8-1090
				15	4-1134	5-1155
	4		.09	16	6-1019	8-1121
				17	6-1083	6-1725
	5	No results				

Diff.	$f=(.45 -1.8u)$	$\dfrac{\text{Strain-diff.}}{f}$	Drill size	$\dfrac{(\text{Length})^{1/2}}{\text{dia.}}$
1999	-.26	-7680	.098	.306
2148	-.26	-8260	.098	.288
2913	-.26	-11,200	.098	.433
-1709	-.26	6560	.098	.306
2398	-.26	-9210	.098	.367
604	-.26	-2320	.098	.202
2841	-.26	-10,930	.098	
1016	-.26	-3905	.098	.288
1021	-.26	-3930	.098	
2102	-.26	-8100	.098	.306
642	-.26	-2470	.098	

TABLE I (cont'd)

Group	Piece	Hole	Length of Line	Gage	Reading Before	Reading After
	6	No results				
	7	No results				
	8		.07	10	5-0348	6-1258
				11	6-0734	5-1806
	9	No results				
	10		.10	8	5-0947	6-0290
				9	5-1028	6-0643
I	I_1	3	.23	18	6-0992	6-1020
				19	4-1201	4-1149
	I_2	2	.20	20	6-0368	5-0738
		3	.21	21	6-1151	7-0862
L	L_1	1	.45	22	7-0801	7-0290
		2	.30	23	7-1167	8-0501
	L_2	1	.25	24	5-1953	5-1216
		3	.15	25	6-1080	6-0870
	JH				5-1121	6-0919
	JE				7-1110	8-0411
	JW				7-1650	8-0600
	JK_1				7-1670	7-1607
	JK_2				7-0930	6-1765
	JF				6-1061	5-1525

Diff.	$f = (.45 - 1.8u)$	$\dfrac{\text{Strain-diff.}}{f}$	Drill size	$\dfrac{(\text{Length})^{1/2}}{\text{dia.}}$
1910	-.26	-7350	.098	.270
72	-.26	-277	.098	
337	-.26	-1295	.098	.332
615	-.26	-2365	.098	
28	-.24	-107	.014	.490
-52	-.24	216	.094	
-630	-.24	2620	.094	.457
711	-.24	-2960	.094	.470
-611	-.26	2350	.094	.683
434	-.26	-1670	.094	.558
-737	-.26	2840	.094	.510
-210	-.26	809	.094	.395
798	-.24	-3320		
301	-.24	-1250		
-50	-.24	208		
-63	-.24	262		
-165	-.24	687		
-436	-.24	1818		

TABLE II

TREATMENT OF THE SAMPLES

| SAMPLE	METHOD OF TREATMENT
8630 Steel	
1	Heated to 1500 degrees F.
	Held for 30 min. at temperature.
	Quenched into oil.
2	Same as No. 1.
3	Same as No. 1.
4	Same as No. 1.
Group A	Same as No. 1.
24S-0 Aluminum	
Group I	Heated to 925 degrees F.
	Held for 30 min. at temperature.
	Quenched into cold water.
Group JH	Cold reduced 48%
Group JE	Cold reduced 51%
Group JK	Cold reduced 62%
Group JW	Cold reduced 36%
Group JP	Cold reduced 43%
Dowmetal	
Group L	Cold reduced 15%

TABLE III

POISSONS RATIO:

8630 Steel - - - - - 0.34

Aluminum - - - - - - 0.33

Dowmetal - - - - - - 0.34

PLATE II

Residual Strain

Micro-inches per inch
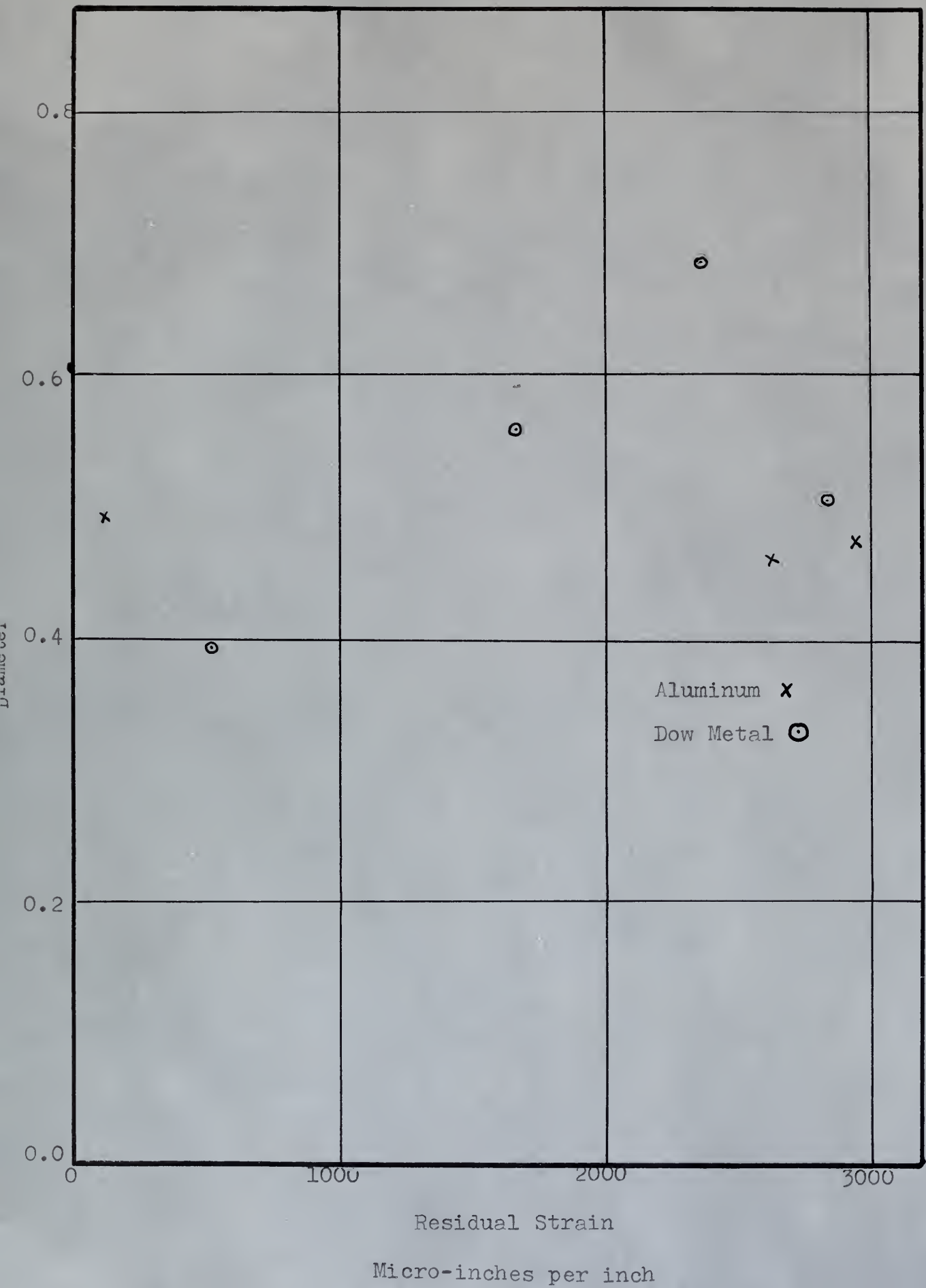
CONCLUSIONS OF THE INVESTIGATION

The results of these experiments with the
brittle lacquer as a measure of residual stresses
yielded no definite results as far as quantitative
measurements are concerned for one of the following
reasons: Either the brittle lacquer method is of
little value in estimating stresses, or the method
used to find the residual strains is not satisfactory.
It is the opinion of the authors that the latter reason
is the chief cause of the indefinite results obtained.
However, inability of the lacquer to show strain
patterns on the greatly reduced aluminum samples has
led the authors to look upon the brittle lacquer
method with caution even as a qualitative indicator
of residual strains. In the use of the electric
strain gages there is always the uncertainty as to
the magnitude of the strains induced by cutting away
the gage. For this reason, it is felt that some other
method of finding the residual strains should be em-
ployed before a definite decision can be reached as
to the value of the brittle lacquer method for quan-
titative measurement of residual strains.

There are two other procedures which could
be used to measure the residual strains. One method

is the use of X-ray techniques and the other method
is the use of high temperature strain gages. The
first method is outlined in reference "G". Since
this method involves much expensive equipment and
study in the operation of the equipment, it was
not readily available for use in this investigation.
The second method has greater possibilities. The
construction, use, and calibration of these high
temperature gages are outlined in reference "D".
The procedure to be followed if this latter method
were to be used would be to place the high temper-
ature strain gage on the sample in its condition
of high residual strain. Then place the piece in
a furnace at an elevated temperature in order to
relieve the stresses in the piece as described in
reference "I". Since the gage could withstand the
high temperature involved, a comparison of the
resistance readings of the gage before and after
stress relief would measure the residual strains.
This method should be especially accurate as it
involves no additional strain due to cutting.
However, there is one serious obstacle to the
use of this method which must be overcome; that
is the long baking period totaling 32 hours at
250 degrees F. which is specified after placing

the gages on the sample. It should be possible
to place the gages on the sample without resorting
to such high temperature baking. This drying period
undoubtedly would contribute considerable stress
relief. Perhaps a longer drying period at room
temperature would suffice. If a solution to this
problem could be found, the measurement of residual
strains could be easily accomplished.

During the course of the experiments it
was noted that cracks of varying intensities were
formed with approximately the same length. Some
of the patterns formed were considered to be crazing.
However, other investigators identified these pat-
terns as strain indications as illustrated in refer-
ences "A" and "B". The patterns shown in the pictures
taken of some of the plates in the authors' experi-
ments are not of this character. The authors feel
that there should be some distinction made between
the strong patterns and the weak ones. As they were
unable to get any satisfactory results due to the
difficulties in measuring the residual strains with
the SR4a strain gages, it was impossible to make the
proper comparison.

The authors feel that more work is warranted
on this topic because the brittle lacquer method of
stress analysis is a simple, yet effective, system.

If it can be proven that the brittle lacquer method
is valuable in measuring quantitatively the residual
strains in metal, a very worthwhile tool will be open
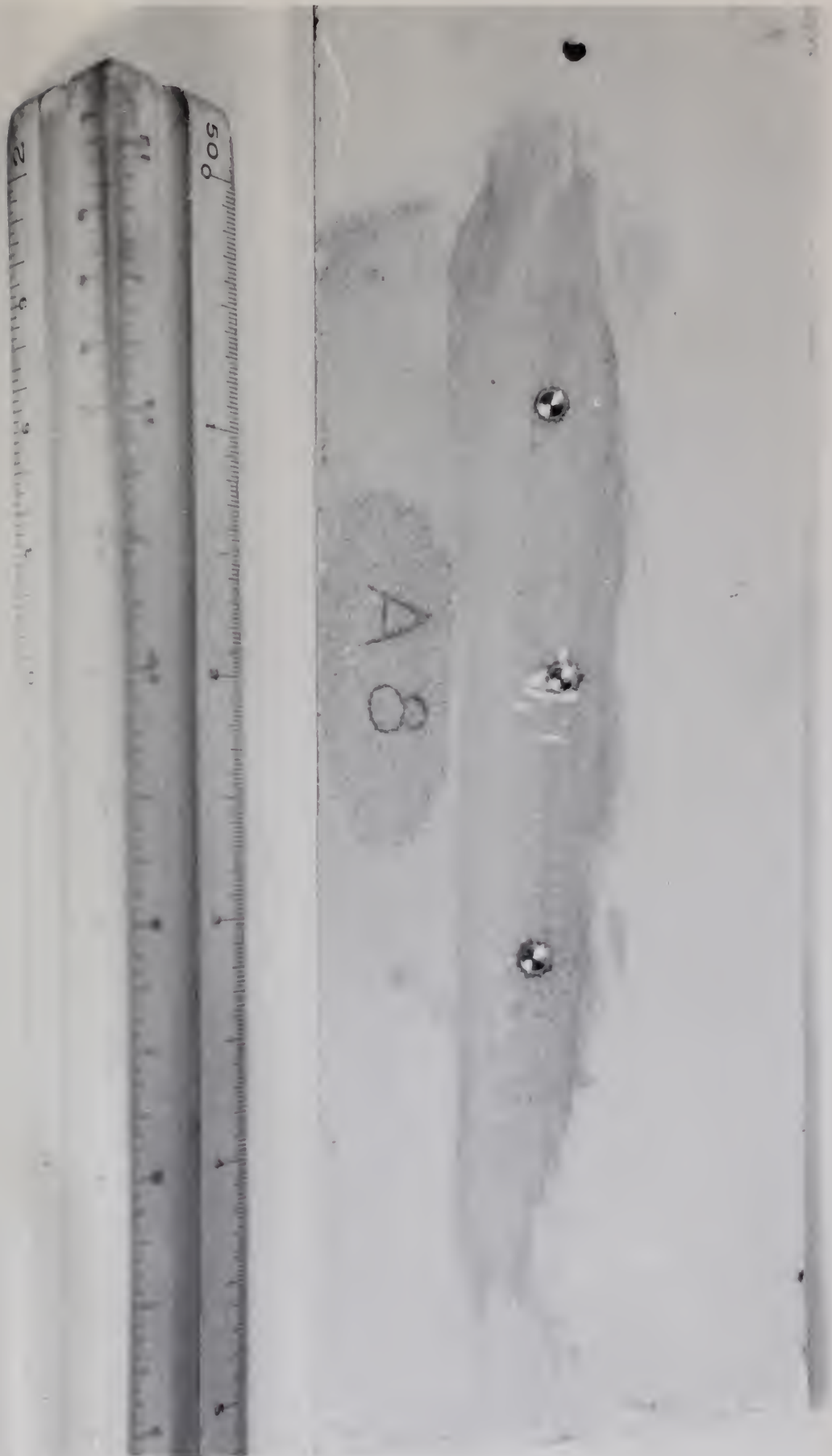for use by the stress analyzer.

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Photograph 1.

Photograph 2.

Photograph 3.

Photograph 4.

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